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Failure Mechanism Analysis of Fuses Subjected to Manufacturing and Operational Thermal stresses

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Abstract

This paper identifies failure mechanisms of axial lead fuses subjected to real field ambient thermal profiles by finite element simulations and experimental testing. Experimental observation of failed fuses attributes fatigue failure of fuses to breakage of the fuse element. The fuse elements consistently fail at the notches adjacent to the end caps accompanied by a localized out-of-plane bend. Identification of the failure mechanism motivates a comprehensive thermo-mechanical study of the fuse deformation response prior to failure, which is rather involved due to the complex interactions of the fuse components, and residual effects of manufacturing processes. An investigation on the pre-operational state of fuses evaluates damage introduced during manufacturing of the fuse. In specific, the work simulates soldering induced residual stresses and addresses their impact on the fatigue damage and lifetime of the fuse. In the paper a lifetime model of the fuse is proposed and tested.

1. Introduction

Fuses are safety devices used to protect electrical circuits from excess currents and short-circuit events, and are compulsory components in modern power designs. The fuse includes a highly conductive perforated strip, known as the fuse element, which blow-up in case of short circuit events. The fuse element is enclosed by a protective tubular ceramic case, which is filled with sand to extinguish efficiently the arc that forms during intervention. End caps in each end of the tube and provide electrical contact with the fuse element through a soldered joint.

Conventional approaches to assess fuse reliability against variations of ambient temperature, subject the fuse to five thermal cycles [1] and assume an infinite lifetime with respect to cyclic ambient temperature if the fuse endure these cycles. However, fatigue failure of axial lead fuses has been observed experimentally after just 100-200 thermal cycles due to variations of ambient temperature within the fuse-rated min/max-operating thermal range [2]. During operation of the fuse, it will experience thermal loading from a variety of sources e.g. environmental thermal loading and self-heating due to current flow. Cyclic loading causes successive expansion and contraction of the fuse components, which result in thermal stresses and accumulation of damage. The thermal stresses wear out the fuse over time and become an important reliability concern.

Thermal fatigue and premature fuse element breakage is one aspect of ambient temperature effects on the lifetime of fuses. Another aspect is the influence of ambient temperature variations on fuse characteristics. Ambient temperature variation cause plastic deformation of the fuse element, which gradually accumulates damage and affects electrical resistance of the fuse element. This is an example of fuse ageing, which affects fuse performance, e.g. i^2t characteristics.

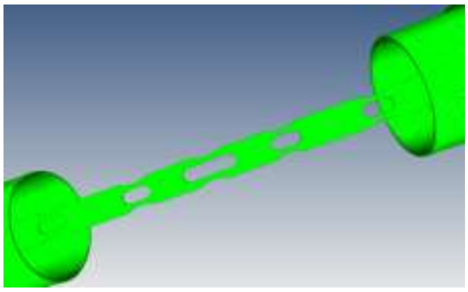
Various attempts have been done to uncover the problem of ageing and lifetime prediction of fuses due to Joule-heating by either continuous currents or pulse currents [3]-[8]. Despite a similar thermo-mechanical response and impact on fuse reliability, little work has been done on fatigue failure and fuse ageing caused by variations in ambient temperature. Such investigations have recently been initiated in [2] through a multi-physics finite element analysis (FEA), and a framework of a methodology has been proposed for lifetime prediction of fuses subjected to real thermal profiles of ambient temperature. However, the root cause of fuse element failure according to previous FE simulations and lifetime models is not consistent with experimental observations regarding fuse element deformation and breakage location.

This paper addresses the uncertainties related to failure mechanisms of fuses by thorough thermo-mechanical FEA of deformation mechanisms of the fuse element, interactions of fuse components, residual effects of fuse manufacturing, and monitoring of cyclic stress- and strain responses. Assessment of fatigue failure is based on Manson-Coffin lifetime modelling and Smit-Watson-Topper (SWT) damage parameters [9]. Fatigue properties of the fuse element are measured experimentally using strain-controlled dynamic mechanical analysis (DMA). The lifetime model is compared to actual test of fuses subjected to cyclic ambient temperatures in a heat chamber.

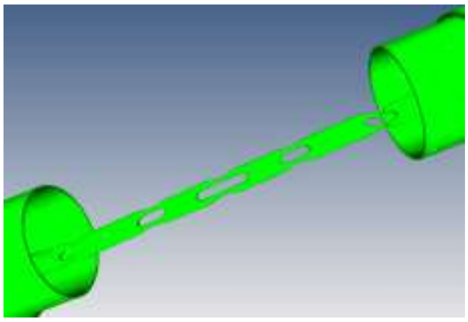
2. Thermal loading and deformation of fuses

The fuse under study is a commonly-used fast-acting axial lead fuse [1], as shown in Fig. 1. X-ray studies of failed fuses that has been tested at cyclic ambient temperature, attribute fatigue failure of fuses to breakage of the fuse element. All the tested fuse elements consistently fail at the notches adjacent to the end caps accompanied by a localized out-of-plane bend, as shown in Fig. 2. Identification of the failure mechanism motivates a comprehensive thermo-mechanical study of the fuse deformation response, which is rather involved due to complex interactions of the fuse components, and residual effects of manufacturing processes.

Fig. 1: Tested axial lead fuses.



(a)



(b)

Fig. 2: X-ray scan of fresh fuse (a), and failed fuse (b), tested at cyclic ambient temperature.

Upon increasing the ambient temperature, the rigidity and relatively low coefficient of thermal expansion (CTE) of the ceramic tube cause

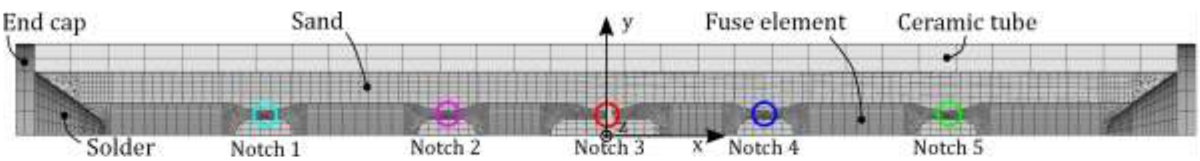


Fig. 3. FE model. Symmetry plane y=0. Critical failure regions are encircled.

compressive thermal strains to develop in the fuse element. The slenderness of the notched fuse element, in combination with a state of compressive membrane strain energy, makes it susceptible to thermal buckling. The surrounding sand impose restrictions on the free deformation of the fuse element and might prevent it from deflecting out-of-plane, depending on the stiffness of the surrounding sand. A FE model of the full fuse structure is built, as shown in a Cartesian coordinate system in Fig. 3; inclusion of all fuse components allows for assessment of their interaction.

The element type and discretization differs between the fuse components, depending on requirements of convergence, simulation accuracy, and computational efficiency. Thermal and structural symmetry is applied at the plane y=0 to gain computational efficiency.

The fuse is modelled using solid quadratic elements with reduced integration order and a pure displacement formulation. The notched regions of the fuse element necessitate a fine mesh due to significant stress gradients, plasticity, and simulation accuracy. Given the ductility and low yield strength of the fuse element, nonlinear plastic behavior needs inclusion in the constitutive formulation.

The plastic material behavior of the fuse element is assumed rate-independent, and uses a Von Mises yield criterion, an associated flow rule, and a multilinear kinematic hardening law for inclusion of Bauschinger effects in case of cyclic plasticity. The material responses of the remaining fuse components are limited to the elastic regime. The solder is a lead-free binary alloy of composition Sn97Cu3. In spite of its low yield strength, solder-plasticity is neglected in the finite element simulation. The effect of solder plasticity proves to have a significant influence at the interconnection of the solder and fuse element, however, the influence drops rapidly as one moves away from the interconnection, and becomes negligible in the regions of interest i.e. the fuse element notches. Effectively, the simplification becomes a reasonable approximation with notable computational benefits. Material properties of the fuse element are available in [10].

Apart from the filler sand, the fuse components are represented as three-dimensional continuums. The intent of modelling the filler sand is to represent the effect of the medium on the fuse element, not to analyze the medium itself. A Winkler foundation [11] represents the mechanical effect of the filler sand on the fuse element. The foundation applies a resisting pressure to the surface of the fuse element, which depends on the foundation modulus and the magnitude of the lateral deflection at the foundation surface.

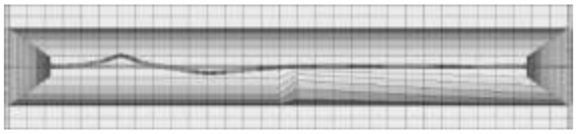


Fig. 4: Plot of the deformations of the fuse components at $\Delta T=40\ ^{0}$ C (25°C to 65°C).

Apart from material nonlinearity, geometrical nonlinearity is also included in the finite element model. The simulations are solved using a full Newton-Raphson procedure, and automatic time stepping- and line search algorithms [12].

The thermal loading of the fuse is introduced by assigning a spatially uniform temperature distribution, which varies with time in accordance with ambient temperatures in real operating conditions. The load introduction invokes an assumption of zero thermal gradients across the fuse components. The assumption is reasonable for low heating- and cooling rates up to approximately 10°C/min. The thermal loading cause deformations and stresses in the fuse components due to mismatches in CTE.

3. Fuse element deformation

The Analysis of fuse element deformations prior to failure is vital for assessment of failure mechanisms and fatigue damage of the fuse. The deformation mechanism of the fuse element becomes complex due to global- and local instabilities under compressive axial loading, and the numerous possible interactions among the fuse components. From a modelling point of view, these conditions enable multiple deformation modes and tighten the demands to the numerical incremental solution procedure to obtain consistent equilibrium configurations.

Analytical modelling of a clamped prismatic beam, would expose a deformed shape resembling a half sine wave, and upon addition of an elastic foundation, the buckling mode would vary between symmetric to antisymmetric modes depending on

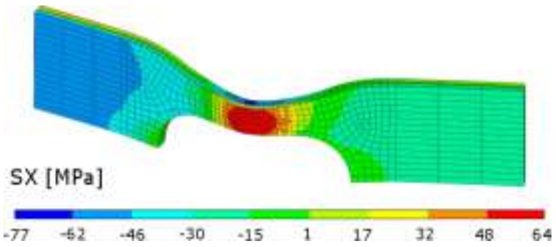


Fig. 5: Deformed shape and contour plot of stresses in notched region at the upper temperature 80°C i.e. ΔT=55°C.

the foundation modulus [12]. Finite element simulations of the actual fuse computes distinct buckling modes of the fuse element depending on the foundation modulus of the filler sand, and proves sensitivity to the introduction of imperfections. The first buckling mode varies from global buckling in terms of half a sine wave or multiple sine waves, to local buckling at sections of reduced width. In the following, a small geometric imperfection is introduced at the leftmost notch of the fuse element, as a lateral perturbation of magnitude L/300, where L represents the length of the fuse element. For these settings, local buckling occurs at the corresponding notch in agreement with experimental observations of fuse element deformation and failure modes.

Considering a thermal ramp from room temperature of 25°C to 65°C, i.e. ΔT=40°C; the deformed shape at 65°C is illustrated in Fig. 4, when scaled by a factor of five. The sharp and local bend at the leftmost notch indicates the onset of plastic straining.

Considering next cyclic thermal loading, by repeatedly heating and cooling of the fuse between room temperature 25°C and 80°C. Fig. 5 shows the temperature and maximum out-of-plane displacement during ten thermal cycles. The initial ramp begins at the origin of the coordinate system and continues to a maximum displacement of approximately 100 μm in the X direction – as shown in Fig. 3 – at ΔT=55°C. Upon cooling the fuse to room temperature, a permanent displacement sets, and after continued cycling, the curves approach a stabilized loop.

4. Residual stresses from fuse manufacturing

By opening new fuses, a pre-tensioned state of the fuse element is observed [2]. Its impact on the thermo-mechanical response of the fuse element should be assessed to fully define the failure mechanism of the fuse element. In the present study, the pretension is assumed to be introduced unintentionally during the manufacturing of the fuse, upon soldering the fuse element to the end caps. A residual stress analysis is performed to assess the effect of soldering induced pretension on the failure mechanism of the fuse element and its lifetime.

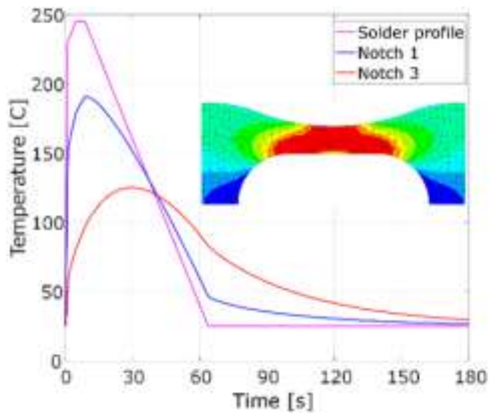


Fig. 6. Residual stress analysis and soldering profile. The counter plot has the similar scale as Fig. 5.

During the assembly of the fuse, the fuse element is soldered to the end caps in two operations. During the cooling process of the last joining operation, the contraction of the fuse components will tighten the fuse element due to restraints by the solidified joints. A soldering profile is imposed at manufacturing time at one end-cap, in accordance with the purple curve in Fig. 6, and the soldering process is simulated using the FE model in Fig. 3.

Once the solder solidifies at T=230°C, the subsequent cooling cause tensile residual stresses to develop in the fuse element. Fig. 6 shows the thermal history during the soldering process at notches 1 and 3. Also included is a contour plot of the residual stress state at notch 1, when the fuse is fully cooled to room temperature. The red contours represent material stressed above its yield limit. A similar contour plot is seen at the remaining notches.

5. Lifetime modelling and fatigue failure identification

The structural response of the fuse is simulated for real field thermal mission-profiles of variations

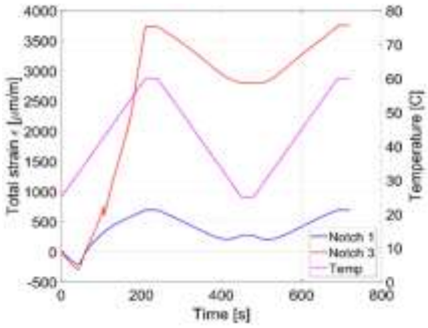


Fig. 7. Strain history at notch 1 and notch 3, and prescribed temperature variation.

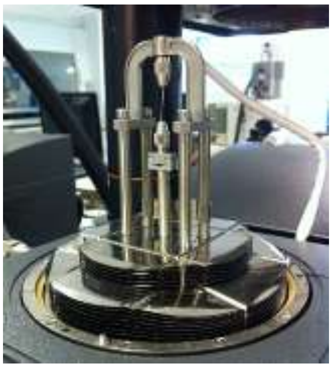


Fig. 8. Experimental setup in DMA Q800.

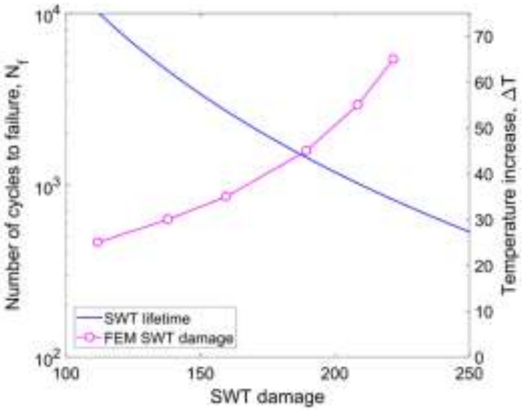


Fig. 9: Relations between SWT damage parameter, lifetime curves and the ambient temperature.

of ambient temperature, and local stress/strain responses are monitored at critical sites for fuse element breakage. FE results of local strain history at notches 1 and 3 are exemplified in Fig. 7. Cyclic stress and strain responses are used in conjunction with a local strain approach to assess lifetime and

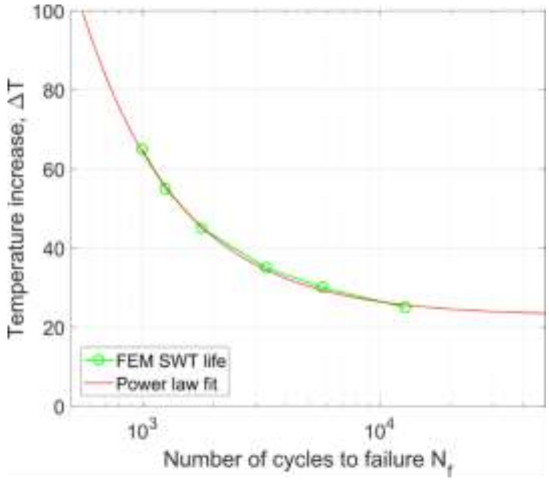


Fig. 10: Ambient temperature increase versus the number of cycles to failure. Green: Computed lifetimes from Fig. 9. Red: Power law curve fit.

location of fatigue failure. A Manson-Coffin type strain-life model with Smith, Watson, Topper (SWT) damage parameters for assessment of mean stress effects, computes the expected number of thermal cycles to failure, N_f, in accordance with Eq. (1) [9].

$$D_{SWT}^2 = \left(\sigma_f'\right)^2 \left(2N_f\right)^{2b} + \sigma_f' \varepsilon_f' E \left(2N_f\right)^{b+c} \quad (1)$$

Wherein $\epsilon_f' = 0.46$ is the fatigue ductility coefficient, $\sigma_f' = 90\text{MPa}$ denotes the fatigue strength coefficient, and $c = -0.5$ and $b = -0.08$ denote fatigue ductility and strengths exponents, respectively [12].

The fatigue parameters of the fuse element are measured from experiments of specimens of the same material using a dynamic mechanical analyzer (DMA) with a setup as shown in Fig. 8. The curves of Fig. 9 provide an indirect relation between the number of cycles to failure and the increase in ambient temperature. An explicit relation between the two can be derived from graphical solutions in Fig. 9. The explicit relation is plotted in Fig. 10, and a power law according to Eq. (2) fits the data set.

$$\Delta T\left(N_f\right) = 6.413e04\, N_f^{-1.063} + 22.88 \quad (2)$$

The equation allows one to compute the maximum allowable ambient temperature variation for a given lifetime, or vice versa through the inverse relation.

6. Conclusion and suggestions

The paper concludes a physical explanation of the root cause of fuse failure under cyclic ambient temperature, and provides a FE model and lifetime model applicable for a general methodology for lifetime prediction of fuses. The impact of manufacturing residual effects on the lifetime of the fuse and its failure mechanism is also investigated. Additionally, the failure mechanism analysis provides valuable information regarding fuse design and manufacturing aspects to avoid failure due to cyclic ambient temperature.

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